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Imaging Technology and Systems

B.S. Jassal and S.C. Jain

Defence Electronics Applications Laboratory, Dehradun-248 001

ABSTRACT

Presents a review of various imaging techniques used in the ground-based airborne and spaceborne systems. It mainly covers the subject on electromagnetic spectrum extending from ultraviolet to microwave region. Discusses various imaging techniques, including their advantages/limitations and available systems and highlights visible, near infrared, thermal infrared and millimeter wave band imaging system developed by the Defence Electronics Applications Laboratory, Dehradun.

1. INTRODUCTION

The imaging sensors reported in the literature mainly cover microwave, millimeter wave, submillimeter wave, infrared, visible and ultraviolet frequency bands. The corresponding wavelength ranges are from 1 mm to 1 m (millimeter wave to microwave) and from 0.4 to 15 μm (the visible and infrared regions). In millimeter wave (MMW) region, the spectral bands corresponding to atmospheric windows are utilised for imaging. In the visible and near infrared band, the most important parameter of the target material is its reflectance; and the reflected sunlight is used for target detection. In the thermal infrared band, the main source of radiation is the black body thermal mechanism by which all objects above absolute zero emit radiation. Most of this radiation is emitted at wavelengths around 10 μm. Detected radiations essentially contain information in two parameters, namely the temperature of the target material and its emissivity. Significant radiation can also be detected in the microwave and MMW bands, and the instrument used for doing this type of imaging is known as passive imaging sensor or radiometer. In the active imaging sensor or radar, the target is illuminated by a source and the return signal is detected.

The National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the National Space Development Agency (NASDA) of Japan, have developed a series of synthetic aperture radar (SAR) systems. The MMW region (30-300 GHz) of the electromagnetic spectrum is also being widely used in imaging applications. Earth resources applications, such as geological mapping and crop monitoring, were the first to utilise MMW radars. Developments are being carried out for MMW imaging radars to be used in a wide range of weapons, including air-to-ground and ground-to-ground missiles. Radiometers at MMW frequencies are also being used in many airborne and ground-based applications. They have been used to provide information over ocean and land for a wide range of environmental investigations; to locate icebergs and detect marine ice spills; and to map agricultural, geological and geographical features. Radiometers have also been developed for providing high resolution MMW images of tactically significant battlefield scenes. Multimode tactical imaging systems are also in use where the target is illuminated by a bistatic noise power illuminator, and imaging is done by a radiometric system. Such systems have many tactical applications, such as missile seeker head, smart munition, etc.

2. ULTRAVIOLET IMAGING

Ultraviolet (UV) imaging has some typical advantages of reflectance and flourescence detection

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and has been used for specific applications. The photographs in the UV band can be acquired with suitable film and filter combinations. The UV detectors are more sensitive than photo film and much less attenuated by any lens. The oil and water films have much better contrast in the UV band. The films as thin as 0.15 μm can be detected in the UV band. Daylight and clear weather is essential for acquiring UV images. The UV is strongly scattered by atmosphere; therefore, at high altitudes, i.e., more than 1000 m, the band starts becoming less effective. Floating patches of foam and seaweed also have bright UV signatures, which can be confused with oil film. This confusion can, however, be eliminated by comparing the UV and visible band images. The active UV systems are also being evolved using tunable laser sources. The spectral distribution of fluorescence can be utilised for detecting broad classes of oils. The active system enables acquisition of the images at night also. An experimental airborne laser remote system for the detection and classification of oil spills has been developed[1] and used for detecting the natural oil seeps along California coast. The UV and IR images have been compared and useful results have been obtained for this purpose.

3. VISIBLE AND NEAR INFRARED SENSORS

The visible and near infrared (NIR) bands have sensitive detectors. The detector arrays have very large number of detector elements (few thousands). The different spectral bands are characterised for specific applications. The spectral range 0.45 - 0.52 μm is used for coastal water mapping, differentiating between soil and vegetation and between coniferous and deciduous trees. The band 2 (in the range of 0.52 to 0.60 μm) detects green reflectance by healthy vegetation while the band 3 (in the range of 0.63 to 0.69 μm) is in the red region and is used to detect chlorophyll absorption of different plant species. The band 4 (in the spectral range of 0.75 to 0.90 μm in the NIR region) is used for biomass survey and water body delineation, while the band 5 (in the range of 1.55 to 1.75 μm) measures moisture of vegetation and can differentiate between snow and clouds. The spectral band 2.08 to 2.35 μm is primarily used for hydrothermal mapping. Highly sensitive charge coupled devices (CCD) arrays with optical butting are used to cover large swath and high resolution in the airborne and satellite missions (Landsat, SPOT, IRS, etc).

3.1 Multispectral Imaging

The conventional multispectral sensors (MSS) use mechanical scanning and separate lenses for different spectral bands and this poses serious problem of inaccurate band-to-band registration and vignetting in the image plane in various spectral bands. DEAL is actively engaged in the development of multispectral scanners using solid-state CCD arrays for multispectral imaging for various applications. Resolution is improved by using linear CCD arrays in the push broom mode of scanning. In this type of scanning, the forward motion of the aircraft or satellite is used to sweep (broom) a linear array of detectors oriented perpendicular to the ground track across the scene being imaged[2]. In a multispectral imaging system, however, separate arrays are used for different bands. Scanning in the along track direction is provided by the aircraft motion and sampling of detectors in the cross track dimension provide scanning in the other dimension to form a complete image. Thus the mechanical scanning is altogether eliminated by using linear CCD arrays. Another important advantage of using linear arrays is higher integration time provided for a particular resolution than that available in a mechanically-scanned imaging system. The integration time available in this system is the product of integration time available in the mechanically-scanned system and the number of resolution elements per scan. Typically, a gain of one thousand in the integration time is achieved by using linear arrays. This improvement results in better

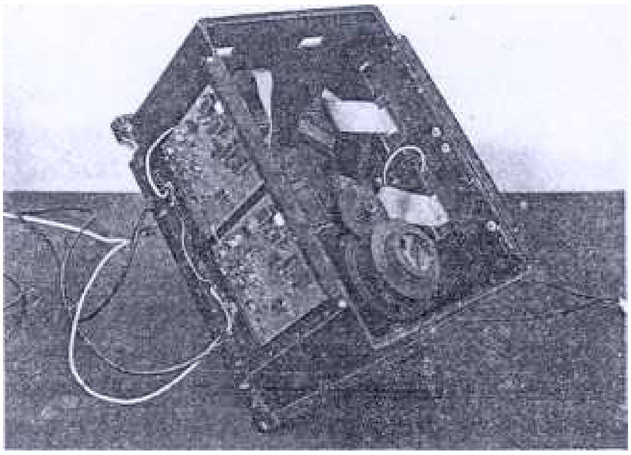

Figure 1. Single lens MSS developed by DEAL.

signal-to-noise ratio of the imaging system. Improved resolution is obtained by using a linear CCD array in the push broom mode. The improvement thus achieved can be utilised for reducing the size and weight of the scanning system without affecting the technical performance. The use of linear array provides better cross track geometric fidelity as the position of each individual photosite is precisely known. This advantage is of greater importance in the case of multispectral imaging since the accurate positioning of arrays for different spectral bands is possible which helps in the registration of the image of different spectral bands. The sensor developed in DEAL uses a single objective lens for imaging the terrain in all the spectral bands[3,4] as shown in Fig. 1. A complex prism having dichroic and total internal reflecting surfaces is used for dispersing the reflected radiation from ground into different spectral bands. A small air gap is provided between the prisms for obtaining total internal reflections. Figure 2 shows the schematic arrangement for the separation of incident radiation in different spectral bands. The CCD sensors cover both visible and NIR bands. The single lens and the complex prism approaches provide accurate band-to-band registration and rugged construction required for airborne and spaceborne systems. The CCD image sensors are being used in almost all the spaceborne surveillance and reconnaissance applications. Table 1 gives the details of various spaceborne visible and NIR imaging systems.

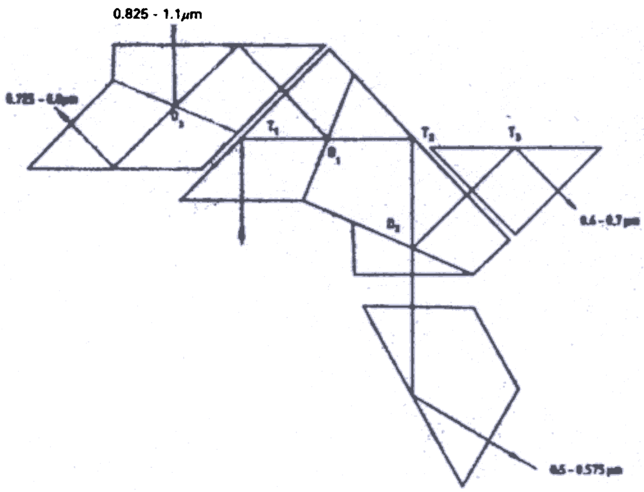

Figure 2. Optics for band separation.

The data rates for some earth observation cameras have exceeded capabilities to record or transmit the data as generated. The solution is data compression, where the original signal is operated on and superfluous bits are not transmitted. Considerable effort has been spent on studying data compression and several

Table 1. Spaceborne visible and NIR sensors

Country/ Satellite	Launch (year)	Exp. life (year)	Height (km)	Sensor/ Bands	Reso-lution (m)	Revisit (day)	Remark
IR[illegible] (India)	1994	3	817	LISS-III(4) PAN	23.6 5.8	24	EOS
LANDSAT-6 (USA)	1993	8	705	PAN (1) THERMAL (1) MSS (6)	15.0 120.0 30.0	16	EOS
KH-12 (USA)	1989		200	VIS, NIR TIR	0.1		RECON
SPOT 2 (ESA)	1990	3	826	PAN (1) MSS (3)	10.0 20.0	26	EOS
MOS (Japan)	1986		909	MSS (4)	50.0	17	EOS
ADEOS (Japan)	1996	3	797	MSS (4)	16.0	41	EOS
KOSMOS TK-350 (Russia)				PAN	10.0		EOS
KOSMOS KVR-1000 (Russia)			213	PAN	2.0		RECON

techniques have been developed to provide compression that has a reconstructed or expanded image that cannot be distinguished from the original. For instance, a camera with 10, 880 pixels per line having a 6 000 lines per second line rate and digitised to 8 bit per pixel, would produce a data stream at 522 megabits per second, a rate well beyond the capability of available recorders and modulators. The data can then be compressed by 8 : 2.5 bits per pixel to an average bit rate of 163 megabits per second which can be successfully recorded and transmitted[5]. Once the data arrives at the ground, it must be expanded back to 8 bits per pixel. It is then ready for analysis on image processing equipment or for hard copy recording.

The optical butting of linear and area CCD arrays has been used to increase the swath area[6,7]. Various methods have been used for obtaining optical butting with or without the beam splitting prism[8]. Optical butting is used to improve the resolution also in case swath is not to be increased. Normally, a trade-off exists between the maximum swath and the highest possible resolution.

3.2 Space-based Telescopes

The various constituents, such as carbon dioxide and water vapours present in the atmosphere make it virtually opaque to IR and other submillimeter wavelength emissions. The astronomers are therefore turning towards spaceborne telescopes which do not have these limitations. The Hubble space telescope is an example of these systems. A new 10 m KECK telscope is scheduled to be launched[9] in 1996. As the size of the spaceborne telescope increases, the problems of precise alignment of primary and secondary mirrors, their support structure and the frequent reorientation become unmanageable. Currently, the focus is on large flexible spacecraft requiring optical precision, i.e., the ability to hold optics within 100 nm or less of the nominal position regardless of the platform vibration. Focal plane arrays are used in cameras operating in the 5-14 μm band for astronomical imaging. The Gallium-doped silicon is used to cover large spectral ranges. Linear arrays of (1 × 1280) *HgCdTe* detectors are planned for satellite spaceborne observation[10]. The advantage of improved signal-to-noise ratio and higher spatial resolutions are achieved by using this technology.

3.3 Underwater Imaging

The recent developments in the solid-state laser diode arrays has yielded more than triple vision capability of conventional underwater flood lighting systems and promise better efficiency and portability in near future. Range gating and synchronous scanning techniques have been used for underwater imaging. In synchronous scanning, a highly collimated laser scans the target and is spatially synchronised with the collecting beam of a single element imaging system. At any instant, the laser illuminates only one resolution element and the reflected energy is detected by the detector. Frame averaging is used to improve the system performance while sacrificing the image frame rate. Currently, available lasers are argon-ion lasers (7W) and frequency doubled *Nd*:YAG lasers. More suitable semiconductor pumped solid-state sources are becoming available. The mechanical scanning needed in the present day systems will also be completely avoided in future using the solid laser diode arrays and the diode pumped frequency doubled solid-state *Nd*: YAG laser systems. An underwater laser imaging system has been developed and evaluated from fixed platform for Naval applications[11].

3.4 Laser Radars for Global Imaging

Global and long-term measurements are needed to establish reliable long-term quantitative baselines, and isolate physical, chemical and biochemical determinants of change. Space-based and high altitude laser radars can measure large scale phenomena, such as stratospheric ozone depletion, global wind pattern distribution of pollutants and stratospheric aerosols produced by volcanic eruptions. Mobile differential absorption lidar has been developed to produce 2D and 3D maps of different gases, including ozone[12]. Global seasonal changes in vegetation can also be detected. The intensity of red, green and blue colours reflected indicates the amount of vegetation. Global database is developed for environmental protection and management of resources. These systems can be supplemented by many smaller and less expensive ground-based systems. AGUSTA and CISE (Italy) can measure resolved flourescence from helicopter to identify gas, crude oil and fuel oil slick on the sea surface.

3.5 Military Applications

Sensors for military applications are required to be small, rugged and light weight. The CCD image sensors not only offer these features but also have the advantages of lower operating voltages, low power consumption and extremely high reliability. By virtue of these advantages, the CCD image sensor systems are fast replacing the traditional electro-optical and photographic devices. Imaging under clear star, moonless night sky conditions (scene illuminations of 10^{-3} to 10^{-4} lux) has been successfully demonstrated with CCD image sensors. The CCD image sensors have been used in satellites, unmanned air vehicles, gun launched, artillery-launched, and cockpit TV systems. The development of CCD image sensors for laser homing and warning system, planetary penetrator probes and unattended ground sensor systems have also been reported. Cameras using CCD image sensors have been successfully tested for 10,000 to 20,000 g accelerations for durations of 2-5 ms for high shock and spin environment need for military applications[13].

4. THERMAL INFRARED IMAGES

Thermal IR images can be acquired during darkness, but not under heavy clouds or fog. The brightest tone indicates high radiation temperature. During day, the water bodies are cooler than soil and rocks, while the situation is reversed at night. Therefore, the thermal IR images are to be properly annotated for the time of the day at which they are acquired. The damp ground is cooler than dry ground at both day and night. The evaporation effect produces cool signatures in the thermal IR band. Green vegetation has a warm signature at night and a cool signature relative to surrounding soil during day. The IR sensitive detector and filter is used to detect the specified radiation (8-14 μm) which corresponds to atmospheric window. The temperature sensitivity of the cooled detectors is typically 0.1 to 0.2 °C and the IFOV is 1-3 m rad. The angular FOV is made panoramic by optomechanical scanners and is 90 °C to 120 °C. The detectors are cooled up to 73 °C for increasing the sensitivity of mercury cadmium telluride and lead tin telluride detectors[14]. Dewars and closed cycle cooling engines are used to maintain the required low temperatures. The IR detectors, including time delay and integration signal processing have been developed by MULLARD.

4.1 Uncooled Infrared Imaging

The pyroelectric infrared detectors provide uncooled, room temperature operation with uniform spectral response from the UV to the far infrared spectral region. They work by absorbing radiation and converting it to heat in a pyroelectric crystal. The changing temperature during heating or coooling of the crystal generates a positive or negative displacement current, like the current in a capacitor, between the detector electrodes. The current is integrated on the capacitance of each detector element until read out by the self-scanning electronics. During readout of each detector element, the total integrated charge is measured. The detector is then reset to its initial bias condition[15].

The time delay and integration (TDI) technique has been used in imaging from moving platforms, like satellite and unmanned air vehicles for improving resolution and signal-to-noise ratio. When the sensor is in motion with respect to the scene being imaged, the TDI provides real advantage in the output signal-to-noise ratio. The improvement is proportional to the square root of the number of steps of integration. Improvement has been obtained in the signal-to-noise ratio by using TDI in the pyroelectric linear imaging arrays. Scanning is performed with the help of a mechanical chopper. The signals of opposite polarity from alternate scans are added in phase. The improvement in signal-to-noise ratio obtained is proportional to the square root of twice the number of integration steps[16]. The fixed pattern noise available in those detectors is cancelled and is practically reduced by a factor of 100 by using this type of TDI scheme[17]. Since the linear pyroelectric detector arrays have useful response from UV to submillimeter wavelength region, these are used for uncooled active millimeter wave imaging also[18]. The system using the linear pyro-arrays avoids the use of mechanical scanning and complex receivers.

5. MICROWAVE IMAGING

Conventionally, the microwave region extends from 0.3 to 300 GHz (1 m to 1 mm in wavelength). However, the frequency range from 30 to 300 GHz (1 cm to 1 mm) is more popularly known as millimeter wave (MMW) region.

Microwave systems are advantangeous over visual and IR systems due to their capability to penetrate clouds, fog, and to some extent rain, smoke and dust encountered in a battlefield. Due to their better penetration in vegetation, they yield information about the lower layers and the ground beneath. Also, the information available from microwave is different from that in visible and IR regions. Hence, the sensors operating in these regions complement each other. The microwave imaging sensors, as already explained, can be categorised as imaging radars and radiometers.

5.1 Imaging Radars

Imaging is one of the important applications of the radar. Military radar reconnaissance systems were the first high quality imaging radars. The same general principles apply to mapping radars in civilian use, although the requirements for military reconnaissance are often more stringent.

The radar systems designed to provide images of the Earth's surface are generally airborne or spaceborne sensors. The motion of the sensor-bearing vehicle provides the relative motion between sensor and target required to perform imaging. There are two generic types of fixed-target imaging systems. The conventional stripmap mode SAR provides wide-area coverage by producing imagery of a strip of terrain illuminated by an antenna whose boresight angle is maximally fixed with respect to vehicle velocity vector. Cross-range resolution is determined by the effective scene rotation during illumination as determined by the antenna azimuth beamwidth. In the spot light mode SAR, antenna boresight angle is decoupled from the vehicle velocity vector to provide longer illumination dwell on the area of interest This approach provides for finer cross-range resolution at the expense of total image coverage. The airborne radar are commonly used in geology, hydrology, crop mapping, forest fire mapping, cartography, monitoring and mapping sea ice, monitoring oil spills in ocean, etc, useful images of moving objects, like solar system's bodies and artificial earth satellites, rotating platforms, aircraft, ships and ground vehicles can be obtained with ground-based radars. The FFT range doppler and extended technique are used for space object imaging applications.

The imaging radars can be classified into three classes, i.e., side-looking airborne radar, scanning radar and synthetic aperture radar.

5.1.1 Side-looking Airborne Radar

The term side-looking airborne radar (SLAR) usually refers to a radar system employing a long antenna, typically 100 to 200 wavelengths, mounted with its long dimension parallel to the longitudinal axis of the aircraft. The antenna points to the side with a beam that is wide vertically and narrow horizontally. The image is produced by motion of the aircraft past the area being covered. The azimuth or cross-range resolution is achieved by the narrow beam width of the physical antenna. Almost all the SLAR systems operate at MMW frequencies due to their capability of providing high resolution.

One of the pioneer MMW SLAR systems, the AN/APQ-97[19], built by Westinghouse, was used for commercial radar mapping. It operated at 35 GHz with pulse duration of a small fraction of microsecond and was capable of producing imagery at resolutions in the 10-20 m range. Some of the other known SLAR systems are: inexpensive SLAR, Motorola AN/APS-94D and EMI P391 operated at 3.2, 3.2 and 0.86 [illegible] wavelengths and with across-track resolution of 12 m, 30 m and 15 m, respectively.

5.1.2 Scanning Radars

The scanning airborne ground mapping radars are primarily used for navigational aids. In addition to providing a map display, the scanning radar is frequently used for terrain avoidance, moving ground target detection, and air-to-ground ranging. Forward looking scanning radars at MMW frequencies are used for detecting static tactical targets. Such radar systems are used from airborne platforms.

The AN/APQ-137 radar, commonly known as MOTARDES (moving target detection system), built by Emerson Electric, is an operational airborne MMW mapping and tracking radar[20]. MOTARDES has demonstrated the ability to detect person walking and a variety of vehicles. The AN/APQ-122(V) is a dual frequency radar developed for C-130E transport aircraft. The equipment provides ground mapping out to 200 nautical miles, weather information out to 150 nautical miles, and beacon interrogation out of 240 nautical miles, when using the X-band radar. Ku-band frequencies are used to provide short-range and high resolution ground mapping to facilitate accurate aerial delivery of cargo. WX-50 at 35 GHz built by Westinghouse Electric, provides a high resolution forward-mapping mode and a terrain-clearance mode for decending to low altitude flight.

5.1.3 Synthetic Aperture Radar

A long-track resolution in synthetic aperture radar (SAR) does not depend on the actual antenna beamwidth and is obtained by signal processing, although SAR is also a side-looking airborne radar. Unlike SLAR system, in SAR the along-track resolution is independent of the distance of the target. Hence, such a system may be used in either an aircraft or a spacecraft.

Perhaps, the first SAR system was launched with SEASAT satellite in 1978. A typical synthetic aperture imaging radar can be described by the shuttle imaging radar (SIR-A)[21], flown on the space shuttle Columbia, consisting of 2.16 × 9.4 m phased-array antenna coupled to the sensor[21]. NASA in conjunction with ESA and NASDA, have embarked on a far reaching programme that goes beyond all previous studies. This programme referred to as the earth observing system (EOS), has placed in orbit a series of remote sensing platforms carrying a wide variety of instruments spanning the electromagnetic spectrum. The prime objective of this programme is to monitor global changes, both human-induced effects and those resulting from natural forces. Some of the well-known SAR systems are listed in Table 2.

RADARSAT is to operate in a polar orbit and will provide important data for agronomists and hydrologists. Low orbit satellites with altitude between 200 to 300 km with very high resolution, less than 200 cm (KH, KVR-100 series) are also launched for military applications. During the Gulf War, United States launched satellites (Lacrosse series) with SAR sensors onboard having resolution of 1-2 m.

5.2 Imaging Radiometers

The imaging radiometer is a highly sensitive receiver capable of measuring low levels of microwave radiations. Radiometers operating at around 1 GHz can be used to map soil moisture content, an important physical parameter in many hydrological, agricultural and meteorological applications.

The MMW imaging radiometers have wideranging military applications. They are capable of detecting metallic and non-metallic weapons, plastic explosives, drugs and other contraband without the necessity of a direct physical search[22]. The technique is completely harmless to the person being observed since it does not require the subject to be exposed to any man-made electromagnetic fields. The ability to covertly observe and track low level aircraft (e.g., helicopters), enemy aircraft may offer a significant advantage in directing anti-aircraft weaponary[23]. Radiometers are able to detect targets against relatively stable backgrounds by virtue of the change in the scene antenna temperature as the target moves across the antenna beam. In practice, it may be preferable to rely on acoustical detection for course direction information and then hand off to the radiometric system for small sector search and precision tracking.

The advent of integrated focal plane arrays of MMW receivers has vastly expanded the applicability of MMW

Table 2. Spaceborne SAR sensors

Country/ Satellite	Launch (year)	Revisit (day)	Height (km)	Band/Frequency (GHz)	Swath (km)	Resolution (m)	Remark
X-SAR (USA)	1994	1	215	X(9.6)	10-45	6.1	RECON
LACROSSE (USA)	1988		200			1.0-2.0	RECON
ERS-1 (ESA)	1991	3	785	C(5.3)	100	25.0	EOS
ENVISAT-1 (ASAR-ESA)	1998	35	800	C(5.33)	56-120	30.0	EOS
ALMAZ (Russia)	1991		280	S(3.0)	[illegible]5-50	15.0	EOS
JERS-1 (Japan)	1992	41	565	L(1.2)	75	18.0	EOS
RADARSAT (CANADA)	1995	16	792	C(5.3)	50-500	28.0	EOS

radiometric imaging. Real-time covert tactical intelligence gathering from ground-based tower-mounted or airborne observation platforms has become possible[23]. The MMW forward-looking imaging radiometer (MFLIR) when used with a forward observer offers a new dimension of flexibility to the gathering of tactical intelligence, like armoured vehicles, aircraft, artillery pieces, trucks, etc. Radiometric terminal homing techniques can be utilised in conjunction with other sensors in a guided missile application. Utilising a range-to-target logic signal, the radiometric mode can be activated at the appropriate time. The radiometric sensor offers relief from some end game target-induced problems for a radar sensor, namely glint caused by target scatterers or nearby corner reflector decoys. The radiometric sensor provides this relief because it primarily works on beam fill and/or target extent and would not resolve out target features until the occurrence of minimum range. WASP and Hellfire are some of the antiarmour seekers developed by Georgia tech[23].

A real-time visual type image of an aircraft runway in low visibility conditions could enable aircraft pilots to land in the presence of zero visibility fog[24]. The MMW radiometry offers a means of producing landing quality real-time runway images through heavy fog. Preliminary indications are that 95 GHz is probably the optimum frequency.

Since image resolution decreases with range, passive ground imaging is generally not practical for tactical navigation and weapons delivery. Bistatic illuminated imaging offers improved contrast on tactical targets while preserving most of the covertness of the passive modes[24]. A few watts of CW noise power spread over the receiver's front end bandwidth can provide substantial contrast enhancement with a very low probability of interest.

The Defence Electronics Applications Laboratory, Dehradun, is engaged in the development of MMW sensors for ground-based and airborne applications. Operating frequency of 35 GHz was selected to obtain a

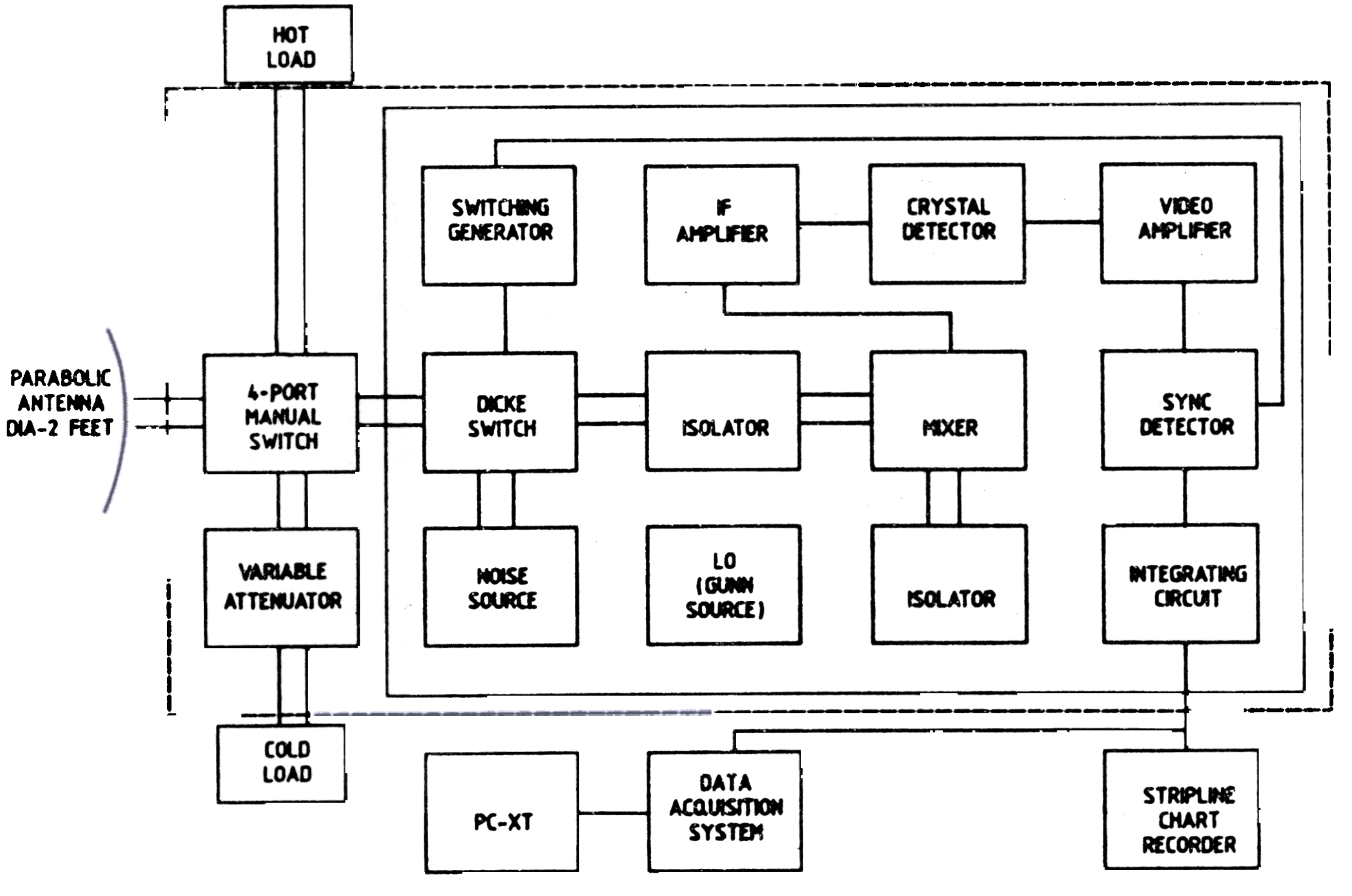

Figure 3. Block diagram Dicke switch radiometer.

high angular resolution. Dicke switch-type radiometric systems at 20 and 30 GHz (Fig. 3) with two feet diameter parabolic dish antenna have been developed[25]. The systems have been used for studying the radio emissions from the clouds, rain and images of terrain.

5.2.1 Satellite Microwave Imaging Radiometers

The microwave radiometry of the earth from satellite began with the launch of Cosmos-243 and Cosmos-384 in 1968 and 1970, respectively. These Soviet satellites, contained nadir-viewing 4-channel radiometers at frequencies between 3.5 and 37 GHz provided information on water vapours and cloud liquid water over the oceans in addition to surface parameters[26,27]. The first US microwave imager was the electrically scanning microwave radiometer (ESMR) at 19 GHz, which was launched on Nimbus-5 satellite, in 1972. This was followed by the second ESMR at 37 GHz on Nimbus-6.

The scanning multichannel microwave radiometer, containing 5 channels with dual polarisation at 6.6 to 37 GHz, was flown aboard the SEASAT and Nimbus-7 satellites, in 1978. Sea surface temperature and wind speed were obtained apart from determinations of ice coverage and open water and global variations of snow cover[28,29]. The latest microwave imager is the special sensor microwave/imager (SSM/I), which was developed as a part of the Defence Meteorological Satellite Programme and was flown aboard the Air Force Block 5D satellite in 1987 and again in 1991. The SSM/I is a conically scanning radiometer having channel from 19 to 85 GHz[30]. The first Japanese microwave radiometer, the microwave scanning radiometer, was launched in February 1987 aboard the Marine Observation Satellite. This was planned for oceanographic applications.

6. CONCLUSION

The present day imaging systems of visible and infrared bands do not involve any moving parts. Linear and area detector arrays provide high resolution, wide coverage and better geometric fidelity. The single lens and beam splitting prisms are used for obtaining accurate band-to-band registration and rugged construction required for airborne and spaceborne applications. The synthetic aperture technology is used in microwave imaging systems for obtaining high resolution and all weather operation. The resolution of such a system is independent of the sensor altitude. The passive radiometers with little illumination have provided much better contrast for airborne mapping applications. The millimeter wave scanning radars owing to their high resolution and large signal-to-noise ratio find special applications in terrain mapping and guidance in military application.

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REFERENCES

1 Maurer, A. & Edgerton, A.T. Flight evaluation of US Coast Guard airborne oil surveillance system. *Marine Technology Society Journal,* 1976, **10,** 38-52.

2. Bist, K.S.; Jain, S.C. & Kumar, V. CCD-based multispectral scanner, *IETE,* 1986, 3(5), 220-23.

3. Jain, S.C.; Bist, K.S. & Santara, S.S. Design of a multispectral sensor. *Opt. Engg.,* June 1994.

4. Santara, S.S.; Bist, K.S.; Sarebahi, K.N.; Malhotra, H.S. & Jain, S.C. Multispectral video data transmission at X-band, International conference on mm wave and microwave (ICOMM-90), DEAL, Dehradun, 16-19, 19-21 December, 1990.

5. George, R.L. Airborne tactical reconnaissance moves to electro-optics. *Photonics Spectra,* 1988, 113-18.

6. Jain, S.C. & McDuff, O.P. Optical butting of linear arrays in a new configuration. *IETE,* 1988, 166-169.

7. Jain, S.C. & McDuff, O.P. Optical butting of matrix arrays. *SPIE,* 1988, **979,** airborne reconnaissance XII.

8. Jain, S.C.; Gohri, V. & Mehta, S.D. Butting of linear arrays without beam splitting prisms. Conference on emerging optoelectronic technologies, IISc, Bangalore, 399-402, December 16-20, 1991.

9. Hugh, B. A clear view sought for large spaceborne telescope. *Photonics Spectra*, 1991.

10. Infrared detectors for military applications. *Philips bulletin*, 1979, **12.**

11 Kaplan, H. Expanding capabilities of underwater imaging, *Photonics Spectra*, 1992, 92-94.

12 Richard, J.B. Laser radar takes the measure of global environmental needs. *Laser Focus World*, 71-77, May 1993.

13 Jain, S.C. & Bist, K.S. Military applications of CCD-based image sensors, *IETE*, 1986, **3**(12), 591-96.

14 Versatile detectors meet IR-imaging needs. *Laser Focus/Electro-optics*, 1988, **165**.

15 Pyroelectric self-scanning infrared detector arrays. *SPIRICON Bulletin*.

16 Jain, S.C. & Santara, S.S. Time delay and integration of a linear pyroelectric arrays, SPIE , 972, infrared technology XIV, 1988, 207-11.

17. Jain, H.S.; Malhotra, K.N.; Sarebahi. & Bist, K.S. Fixed pattern noise cancellation in linear pyro arrays, SPIE 's International symposium on optical engineering and photonics on aerospace sensing, April, 1991, Florida, USA.

18. Jain, S.C. *et al.* Active MMW imaging with linear detector arrays. International conference on MM wave and microwave (ICOMM - 90), DEAL, Dehradun, 12-15, December 19-21, 1990.

19. Microwave remote sensing , active and passive, Addison-Wesley Publishing Company, FT Ulaby, AK Moore, AK Fung, 1981, **1**(1), 42-48.

20. Curie, N.C. & Brown, C.E. Principles and applications of millimeter wave radar, Chapter 15, 1987, 701-12

21 Introduction to the physics and techniques of remote sensing by Charles Elacni, Wiley series in remote sensing, 1987, 214-21.

22. Huguenin, G.R. Detection of concealed weapons and contraband using passive millimeter wave imaging, millimeter and submillimeter components instruments and subsystems. Millitech Corporation.

23. Morton, T.P.; Newton, J.M. & Gagliano, J.A. Millimeter wave radiometry, *SPIE*, **337**, *Millimeter Wave Technology*, 1982, 159-69.

24 Poradish, F.J. & Halbe, J.M. Millimeter wave radiometric imaging, *SPIE*, **337**, *Millimeter Wave Technology*, 1982, 170-80.

25 Jassal, B.S.; Gupta, G.D.; Verma, A.K; Singh, M.P. & Singh, Lal. 20/30 GHz radiometric propagation measurements in India, 1994, IEEE AP-S. International symposium and URSI Radioscience Meeting, University of Washington, Seattle, Washington, June 19-24, 1994.

26. Akvilonova, A.B.; Kaluza, B.G. & Mitnik, L.M. Latitudinal distribution of the integral water content of clouds over the earth according to measurements data from the COSMOS-243 satellite. *Atmos. Oceanic Phys.*, 1971, **7**(2), 139-44.

27 Akvilonova, A. Ye.; Kaluza, B.G. & Mitnik, L.M. Latitudinal distribution of the integral water content of clouds over the Earth according to measurements data from COSMOS-243 satellite. *Atmos. Oceanic Phys.*, 1971, **7**(2), 139-44.

28. Njoku, E.G. & Swanson, L. Global measurements of sea surface temperature, wind speed and atmospheric water content from satellite microwave radiometry. *Mon. Weather Rev.*, 1983, **111**, 1977-87.

29. Wentz, F.W.; Mattox, L.A. & Peteherych, S. New algorithms for microwave measurements of ocean winds : Application to Seasat and the special sensor microwave imager. *J. Geophy. Res. 91*, 1986, 2289-307.

30. Hollinger, J.; Lo, R.; Poe, G.; Savage, R. & Pierce, J. Special Sensor Microwave/Image User's Guide. Naval Research Laboratory, Washington, December 1978.